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Service life prediction of RC structures based on correlation between electrochemical and gravimetric reinforcement corrosion rates

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ABSTRACT

This paper outlines a comprehensive experimental investigation to establish relationships between electrochemically and gravimetrically measured reinforcement corrosion rates generated through a comprehensive experimental program. The investigation is based on testing a total number of 486 reinforced concrete (RC) specimens prepared using coarse aggregates obtained from *two* distinctly different sources of aggregate and considering three levels of *five* design variables (*namely*: cementitious material contents, water to cementitious materials ratios, fine to total aggregate ratios, concrete-cover thicknesses, and exposure to chloride-solutions). The correlation between corrosion rates measured using electrochemical method to that using gravimetric method is established and used to convert electrochemically measured corrosion rate into equivalent but more accurate gravimetric corrosion rate that would be valuable for service life prediction of RC members RC structures in corrosive environments. The experimental program and sample numerical results obtained are outlined and summarized. Then a methodology for *predicting remaining service life* of corroding RC members is illustrated through a numerical example.

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1. Introduction

The presence of chloride ions in a concrete mixture, contributed by its constituents, or due to natural transport processes has been observed to play a critical role in initiating and maintaining the progress of reinforcement corrosion in RC structures. Corrosion of reinforcing steel bars has been known worldwide to be the main cause of accelerated deterioration of many RC structures and some premature structural failures even well-before their designed service life [1]. Numerous research reports and field studies have identified chloride products and chloride ions in particular as being responsible for the corrosion of steel bars in concrete [2]. The resulting corrosion products have larger volume and induce strains and stresses, which can cause cracking and spalling of the concrete cover along with loss of bond between the steel and concrete. A reduction in the rebar diameter and loss of the bond due to reinforcement corrosion can cause a significant loss of load-bearing capacity of the corroded RC members [3] and may therefore shorten the service life of the structure.

After corrosion initiates, corrosion rate is a key predictive parameter to determine the remaining service life of corroded RC structures exposed to a corrosive environment [4] and the method of electrochemical linear polarization resistance (LPR) is often used as a non-destructive method to monitor quantitatively general corrosion and galvanic corrosion. It is sometimes used to qualitatively monitor localized pitting corrosion. The main advantages of electrochemical techniques include sensitivity to low corrosion rates, short experimental duration, and well-established theoretical basis. However, the electrochemical LPR technique is found to have some experimental errors such as error due to Ohmic drop during polarization. On the other hand, the method of gravimetric weight loss (GWL) measurement is an alternative destructive technique to determine corrosion rate with more accuracy [5]. But the destructive nature of the gravimetric weight loss (GWL) method makes the non-destructive LPR method, despite of its intricate practical limitations, more commonly utilized for assessing the rate of reinforcement corrosion.

In LPR method, the steel bar is polarized by the application of a small perturbation to the equilibrium potential through a counter electrode. The polarized surface area of the steel bar is assumed to be that area which lies directly below the counter electrode, but there is considerable evidence that current flowing from the counter electrode is not confined to the polarized area and may spread laterally over an unknown large area of the reinforcing steel, with the natural consequence of inaccurate estimation of corrosion rate [4]. On the other hand, gravimetric (weight loss) measurement as a destructive test, when conducted in controlled laboratory conditions serves as the most reliable reference method. It is simple, but is also a time-consuming technique for the determination of

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Nomenclature

A	exposed surface area of rebar (cm^2)
B	stern–Geary constant (mV)
β_a	anodic Tafel constant (mV)
β_c	cathodic Tafel constant (mV)
C_L	chloride concentration (%)
C_s	surface chloride concentration (%)
C_{th}	threshold chloride concentration (%)
C_v	concrete cover (mm)
D	diameter of rebars (mm)
D_{app}	chloride diffusion coefficient (m^2/s)
F	Faraday's constant (96487 Coulombs)
I_{corr}	corrosion current density ($\mu A/cm^2$)
$I_{corr,e}$	electrochemically measured corrosion current density ($\mu A/cm^2$)
$I_{corr,g}$	gravimetrically measured corrosion current density ($\mu A/cm^2$)
J_r	corrosion rate ($g/cm^2/yr$)
P_r	corrosion penetration rate ($\mu m/yr$)
Q_{cr}	amount of corrosion products needed for causing cracking (g/cm^2)
R_p	linear polarization resistance ($k\Omega\, cm^2$)
t	age of structure (yr)
t_{cr}	time to corrosion cracking (yr)
t_p	corrosion initiation time (yr)
t_{RL}	residual life (yr)
T	exposure time (h)
W	equivalent weight of steel (27.925 g)
W_L	weight loss (g)
W_i	initial weight of the bars before corrosion (g)
W_f	weight of the bars after cleaning all rust products (g)

corrosion rate. The weight loss measured is converted to a uniform corrosion rate over the exposure period. It has been proposed that the combination of the weight loss method and the polarization resistance method offers means of quantitative corrosion analysis. However, studies on the relationship between the two methods are limited and most studies were conducted on different sets of specimens [6].

Accurate value of in situ measured corrosion rate is needed to carry out the service life prediction of RC structures exposed to corrosive conditions. As mentioned earlier, the accuracy of reinforcement corrosion rate measured electrochemically is invariably unreliable because of the difficulties and errors frequently involved in experimental measurements. Therefore, it is highly desirable to correlate the electrochemically measured corrosion rate with gravimetrically measured corrosion rate so that the electrochemically measured values of corrosion rate can be converted into the more reliable equivalent gravimetric corrosion rate to be used for service life prediction. This paper presents: (i) an overview of the experimental program that was used to compare corrosion rate values using LPR and GWL methods; (ii) statistical analysis and initial results on the correlation between electrochemically and gravimetrically measured reinforcement corrosion rates obtained using compiled experimental data; and (iii) a computational approach for service life prediction of RC structures in a specified corrosive environments.

2. Experimental program

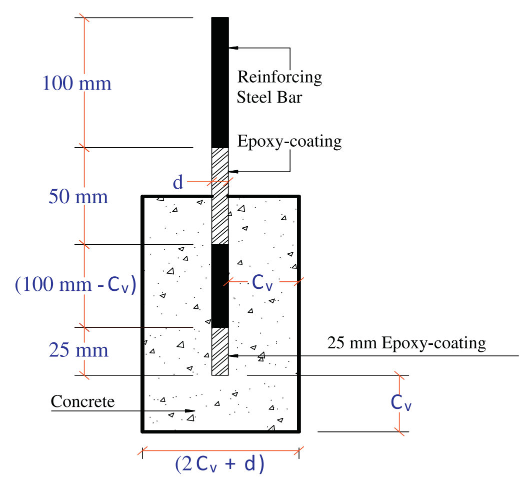
2.1. Materials

ASTM C 150 Type I Normal Portland cement was used with 8% replacement by silica fume for all the mixtures. Coarse aggregates from distinctly different sources located in the *eastern* region and in the *western* region of the Kingdom (*namely*: Abu Hadriyah quarries and Taif quarries) were used [7]. The specific gravity and water absorption, needed for mix design, were determined using ASTM C128 [8] and abrasion test results of coarse aggregates were obtained in accordance with ASTM C131 [9]. Dune sand was used as fine aggregate.

2.2. Test specimens and concrete mix design

Steel bars of diameter 16 mm were placed centrally in each one of the 486 cylindrical concrete test specimens [10] of height 150 mm and diameters 66 mm, 91 mm and 116 mm, with three different cover thicknesses 25 mm, 37.5 mm and 50 mm. The test specimens were prepared to evaluate corrosion rate and epoxy coating was applied to the steel bar at the bottom and at the interface between the concrete and air as shown in Fig. 1a.

The absolute volume method was used for the concrete mix design and the quantity of each constituent was calculated on the basis of weight. All the concrete specimens were prepared with cementitious materials (92% Normal Portland cement and 8% silica



(a) Details of a typical test specimen.

(b) Test- specimens in exposure tank.

Fig. 1. Details of a typical test specimen and test specimens exposed to chloride solution.

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